NATURAL AND ANTHROPOGENIC FACTORS AFFECTING GLOBAL AND REGIONAL CLIMATE

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With the advent of Earth-orbiting satellites to monitor our planet and spacecraft that study the sun, an active International joint project to monitor the Sun – Earth (Solar Terrestrial) environment has evolved. Coupled with an ever increasing computational capability, we are now able to study the many factors which influence the weather (the day-to-day variations in temperature, precipitation, and storm activity) and climate (seasonal and annual patterns of weather) that characterize the New England region. In addition to recorded data and observations from space, recent advances in the study of ice core data, tree rings, lake and bog sediments, and other forms of proxy data now allow us to understand how our global and regional climates have changed in the past.

In this chapter, we discuss some of those factors which are known to have affected the New England climate in the past, so that we can better understand potential consequences of future climate variability and change. First, we discuss solar factors which operate on times scales from days to millennia and consequences of these variations in New England. In many cases the magnitude of solar radiative forcing variations is small, but a number of mechanisms including changes in greenhouse gas concentrations may amplify the effects of solar variations on the earth's climate. Variations in volcanic activity and distribution of aerosols can also affect global and regional climate and are discussed here, along with a brief consideration of the impact of changing land cover types. Finally we consider the recent rate of greenhouse gas increases due to human activity, and the possible consequences of altered atmospheric patterns such as the North Atlantic Oscillation (NAO) on climate in the New England region.

Variations in Solar Forcing and Consequences on Earth

The Sun affects Earth in many ways. Phenomena on the Sun can impact the local space (near Earth) environment, resulting in changes in "space weather." These variations can in turn affect our everyday lives. Very energetic solar events like solar flares and coronal mass ejections (CMEs) release charged particles that affect communications on Earth, including radio and television, navigational systems, Automatic Teller Machines, and even "pay-at-the-pump" operations.

The Earth's rapidly fluctuating magnetic fields stimulated during periods of solar activity can induce currents in long pipelines, affecting flow meters and pipeline corrosion. These geomagnetic storms also induce currents in power grids that are harmful to transmission equipment, sometimes resulting in power outages.

Do these phenomena affect climate changes on Earth as well?

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Orbital Variations and Glacial and Interglacial Cycles

The New England region was located at the southern end of one of the major northern hemispheric regions of continental ice sheet growth. The New England region was covered by this massive ice sheet on several occasions. This latest period of glaciation is known as the Pleistocene epoch, a period characterized by oscillations between glacial maxima or ice ages (colder periods in which the glaciers extended over New England) and interglacial ages (warmer periods in which the ice sheets retreated and/or disappeared). These glacial maxima were about 10 -12°F (~6-7°C) colder than interglacial temperatures.

Figure 3.1 presents data derived from the Antarctic ice cores for the past 160,000 years. Measured concentrations of CO_2 and CH_4 (methane) are plotted over time, along with a proxy record of temperature derived from oxygen isotope ratios measured in bubbles trapped in the ice. Note that portions of two glacial maxima and two intervening interglacial periods can be seen. Although the present level of CO_2 is over 370 ppm (parts per million), note that at no other time during the past 160,000 years have CO_2 levels been above 300 ppm. These past climate fluctuations are believed to be related to changes in Earth-Sun relationships known as *Milankovitch* cycles, as well as possible cyclical variations in the energy output of the Sun, and natural fluctuations of CO_2 and CH_4.

The *Milankovitch* cycles include changes in: 1) the shape of Earth's orbit around the sun (between circular and slightly elliptical) thereby affecting the distance between the Earth and the Sun; 2) the tilt of Earth's axis relative to the orbital plane (approximately a 41,000 year cycle), and 3) the distance between the earth and the sun at a given point of the year (on approximately 21,000 cycle years). The total length of these orbital cycles (approximately 100,000 years) matches well the length of cycles between ice ages (figure 3.1).

Variations in Solar Activity During Recent Centuries

Variability in solar output may also have important consequences on global and regional climate. Galileo used his primitive telescope to describe large numbers of sunspots as early as 1610AD. During the period from approximately 1645-1715AD, very little sunspot activity was recorded, a period known as the Maunder Minimum (Figure 3.2). The Maunder Minimum coincides loosely with the beginning of a longer period known as the "Little Ice Age" (see below).

Figure 3.2 shows the sunspot cycle from 1610 to 1998. This periodic solar behavior is echoed in some locations by cycles in tree ring growth, yearly rainfall in the Northern Hemisphere, and in variations of dust and chemical residues found in ice cores.
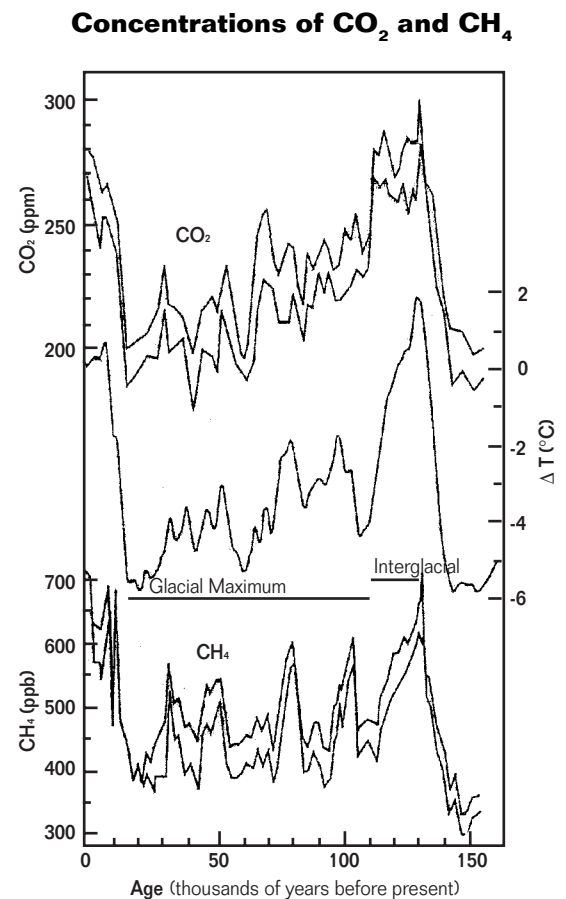
Concentrations of CO_2 and CH_4

FIGURE 3.1

Data on concentrations of CO_2 and CH_4, as well as temperature inferred from O_2 isotope ratios. Modified from the Ice core Working Group (1998). It is important to note that recent CO_2 levels exceed 370 ppm and CH_4 levels exceed 1800 ppb. Note that interglacial periods are relatively short (20,000 years) when compared with the longer glacial maxima.

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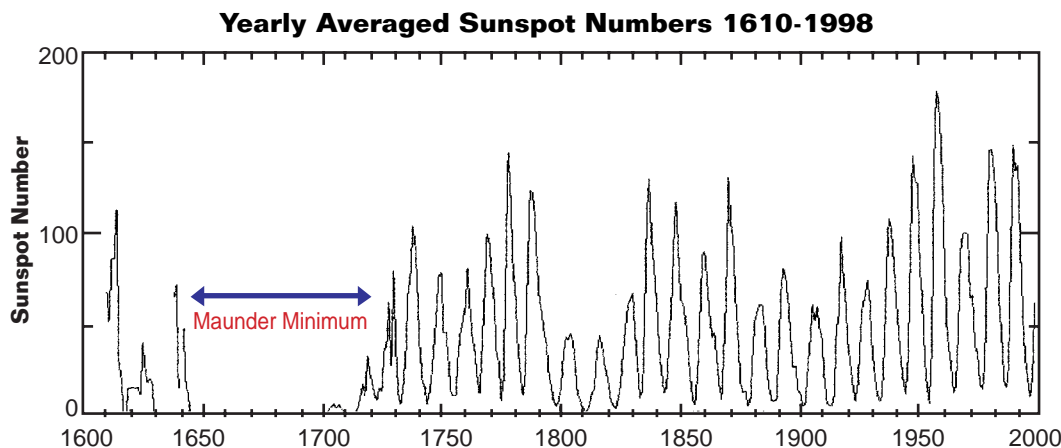
Yearly Averaged Sunspot Numbers 1610-1998

The timing of the Maunder Minimum and the initiation of the Little Ice Age is of particular interest. Unfortunately, there are no sunspot records prior to 1610, but many scientists agree that the Maunder Minimum is only a partial explanation for that period of cooler temperatures. During the Little Ice Age, Eskimos extended as far south as Scotland, it snowed in Ethiopian mountains and orange groves in China died. Norse colonies established during the Medieval Warm Period (900-1400 AD) on Greenland failed during the Little Ice Age due to heavy pack ice which prevented supply ships from reaching them. The Anasasi people of the American southwest abandoned their pueblos at the beginning of the Little Ice Age. Although there appears to be a statistical correlation between sun spot cycle and weather patterns, no satisfactory explanation provides a clear physical mechanism for these associated changes.

Land Cover and Land Use Change Affect the Impact of Solar Forcing and Greenhouse Gas

When sunlight strikes the land surface, one of several things can happen. If the surface is extremely bright, much of the sunlight is reflected back to space through the atmosphere. This happens when the land surface is covered with snow, or when the surface is obscured with cloud cover. Little surface heat is produced when sunlight strikes a bright surface. If the surface is dark, however, much of the sunlight is absorbed, generating heat and warming the dark surface. Dark surfaces such as soil and rock are warmed by incoming sunlight, becoming heat sources which return heat to the atmosphere, even after sunlight is no longer shining on them. Some dark surfaces behave differently, as in the case of forest cover. The forests absorb much of the sunlight as part of the process of photosynthesis. In the process of light absorption by leaves, heat is also produced but evaporation of water vapor through stomates (transpiration) cools the leaves. Thus, although fairly dark, a forest canopy actually cools the surface, rather than warms it. Forests represent a land cover type that acts as a heat sink (cooling the surface) rather than a heat source (warming the surface and surrounding atmosphere).

Thus when we cut down large tracks of forests, and replace them with urban land cover (shopping malls, parking lots, buildings, roadways, etc.), we are converting a heat sink into a heat source. The concept of an urban "heat island" is well known, and changes in land cover and land use over time can contribute significantly to local and regional warming trends.

> The overall effect of sulfate aerosols is to cool an area by limiting the amount of sunlight that reaches the surface.

Sulfate Aerosols Have a Cooling Effect on Climate

Fine droplets of sulfuric acid in the atmosphere (sulfate aerosols) develop when sulfur compounds such as sulfur dioxide (SO_2) combine with atmospheric water vapor. The sulfur in the atmosphere can be either natural in origin (typically from volcanic eruptions) or anthropogenic (typically from the combustion of fossil fuels rich in sulfur, such as fuel oil or coal). The sulfate haze which limits visibility during summer months in the New England region is typically the result of SO_2 emissions from coal-fired power plants in the midwest combining with humid air (Figure 3.3).

Just as bright land surfaces reflect sunlight back through the atmosphere, sulfate aerosols act as a reflective component in the atmosphere, limiting visibility and reflecting sunlight. The overall effect of sulfate aerosols is to cool an area by limiting the amount of sunlight that reaches the surface. As is often the case with volcanic eruptions, sulfate aerosols produced enter the stratosphere and can remain in the atmosphere for prolonged periods of time. "The year without summer," 1816, was characterized by snowfalls in every month of the year across the New England region. This followed by one year the eruption of Tambora, in 1815, which ejected large amounts of debris (including sulfate aerosols) into the stratosphere, cooling the climate worldwide. More recently, the eruption of Mount Pinatubo in 1991 provides a likely explanation of the mid-1990s cooling trend seen in the New England regional temperatures presented in Chapter 2 (Figure 2.1).

Variations in Greenhouse Gas Concentrations Amplify Effects of Other Forcings

Greenhouse gases are gases which are transparent to sunlight, but are not transparent to heat energy, thus trapping heat within an atmosphere containing greenhouse gases. Variations in atmospheric greenhouse gas concentrations may amplify the effects of variations in solar forcing as well as land cover change. To help put recent human-induced increases in atmospheric CO_2 into perspective, it is instructive to consider past variations in greenhouse gases (particularly CO_2) and climate. Instrument measurements of climate variables (temperature, precipitation, storm patterns, etc.) date back to the mid to late 1800s (some temperature records go back to the 1860s). Direct measurements of atmospheric CO_2 concentrations in the troposphere (the lowest layer of the atmosphere) began in 1958 at an observatory on Mauna Loa in Hawaii. Most measurements of other greenhouse gases in the atmosphere such as CH_4 (methane - which is twenty times more powerful at trapping heat energy than CO_2), go back only a few decades.

Fortunately, our understanding of how modern changes in concentrations of greenhouse gases, such as CO_2 and CH_4, may impact

FIGURE 3.3
The view from the summit of Mount Washington, NH on a clear day (8/14/81) and the same view on a hazy day (6/26/80). The light scattering haze is caused by sulfate aerosols which limit visibility and present a health hazard to people and forests alike.

Since CO_2 from fossil fuels has a chemical signature there is no doubt that the increase is due to human activities.

climate can be improved by studying past variations in atmospheric gases and climate in ice cores (Figure 3.1, 3.4). Ice cores collected from the Greenland ice sheet are up to 110,000 years old, while cores from the Antarctic are up to 420,000 years old. In places like Greenland and the Antarctic, analysis of the chemical composition of the ice cores permits analysis of past variations in greenhouse gases in both hemispheres. Temperature can be estimated by using oxygen-isotope ratios derived from the O_2 trapped in the same ice core bubbles used to measure CO_2 and CH_4 levels (Figure 3.1).

Atmospheric CO_2 levels between 270-290 ppm are characteristic of our pre-industrial atmosphere, and also occurred during several previous interglacial periods such as the previous interglacial about 125-115,000 years Before Present (B.P.) (Figure 3.1). During the last 130,000 years, as glaciers advanced over mid-latitude continents in the northern hemisphere, the concentration of atmospheric CO_2 gradually dropped to about 190 ppm due in part to gas solubility in sea water. Colder water holds more gas, and less CO_2 is found in the atmosphere when the ocean surface is cold. Based on recent analyses of Antarctic ice cores, atmospheric CO_2 concentrations began to increase about 1800 yrs A.D. Since CO_2 from fossil fuels has a chemical signat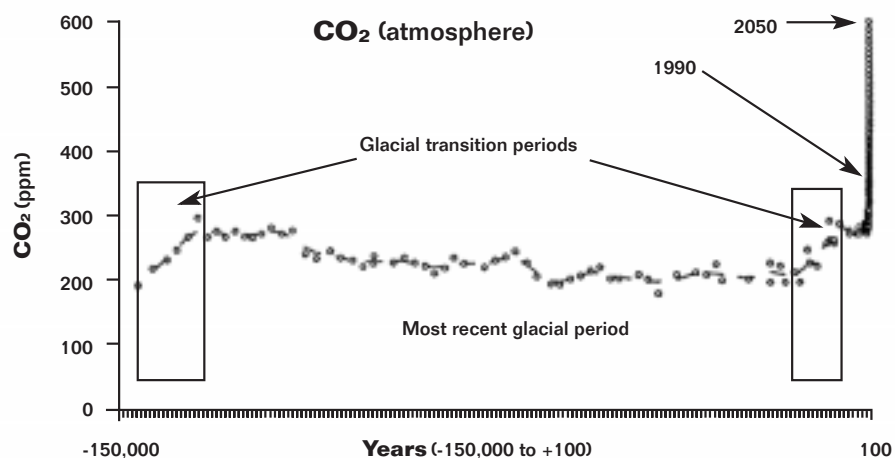ure, there is no doubt that this recent increase is due to the combustion of fossil fuels. As a consequence of fossil fuel use, atmospheric CO_2 concentrations are currently above 370 ppm, now about 30% higher than the 280 ppm level typical prior to the Industrial Revolution (1850s). Current levels are the highest in the last 160,000 years (Figure 3.4).

FIGURE 3.4
Estimates of CO_2 concentrations for the last 150,000 years with a projection to A.D. 2050 based on present-day rates of emission.

Evidence of Rapid Temperature Change

There have been abrupt periods of warming and cooling during the past 160,000 years particularly in the North Atlantic region, but the mechanisms are not well understood. Recent studies document periodic abrupt climate changes in the North Atlantic (recurring in cycles of 1,300 - 1,800 yrs.) based on the study of debris in deep sea sediments. A possible mechanism for this cycle may be related to a 1,800 yr. oceanic tidal cycle with periodic variation in vertical mixing and surface ocean cooling.

Climate reconstructions based on tree ring width and density variations can provide information about past variations in precipitation and temperature. This is accomplished by analyzing variations in stable carbon and oxygen isotope ratios in the cellulose of the wood. Carbon isotope variations in tree rings have been related to variations in the amount of precipitation, while oxygen isotope variations in tree rings can record variations in both air temperature and atmospheric circulation changes.

For the past 1000 years, rates of change in Northern Hemisphere temperature have been estimated by multi-proxy analysis (Figure 3.5). As a result of these and other recent paleoclimate reconstructions, there is little debate about whether we are currently in a period of rapid global warming. The last 100 years can be seen as a period of rapid warming in the northern hemisphere relative to temperature changes during the last 1000 years.

Computer models used in the New England Regional Assessment suggest that the rapid increase in atmospheric CO_2 due to anthropogenic emissions could be followed by a rate of global warming of an additional 3.2 to 5.1°C (6.0-10.0°F) in the next 100 years. This would represent an acceleration in the rate of warming far beyond the warming experienced in the last century or last millennium, moving us into a range of global temperatures that have not been experienced in over two million years. See Chapter 1 for a sense of what the impacts of such warming trends might be.
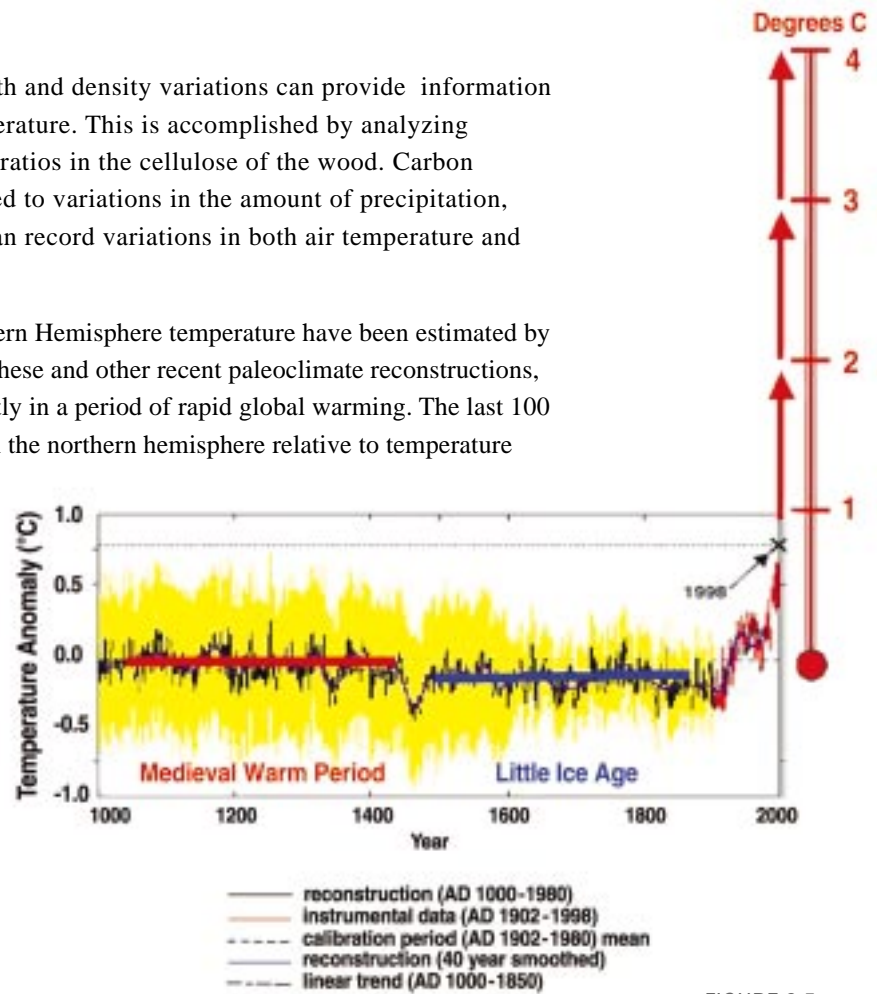

FIGURE 3.5
Northern Hemisphere temperature changes in the last 1000 years.
The yellow marks the range of variability in the date.

Climate Variability and Teleconnections in the New England Region

The El Niño / Southern Oscillation (ENSO) cycle primarily affects low-latitude systems (e.g. the southwestern United States), but is associated with climate variations via teleconnections in other regions of the country. Poor air quality summers over the past two decades correspond to El Niño years. The ENSO variations can be characterized using an index of east-west atmospheric pressure variations across the equatorial Pacific, measured using the Southern Oscillation Index (SOI).

Similar variations in the mass of the atmosphere and resulting atmospheric pressure gradients also occurs over the North Atlantic, and are a prominent factor in the Northern Hemisphere winter climate. The atmospheric-pressure oscillations at the sea surface over the North Atlantic during the past century can be documented in a variety of ways. One can compute a monthly NAO index by measuring differences in monthly mean sea level pressure (SLP) and north–south differences in SLP between the Icelandic Low and Azores High (Figure 3.6).

The winter warming trend in southern New England coastal waters correlates well with the transition from a prolonged negative NAO winter index phase to a positive phase between 1950 and 1990.
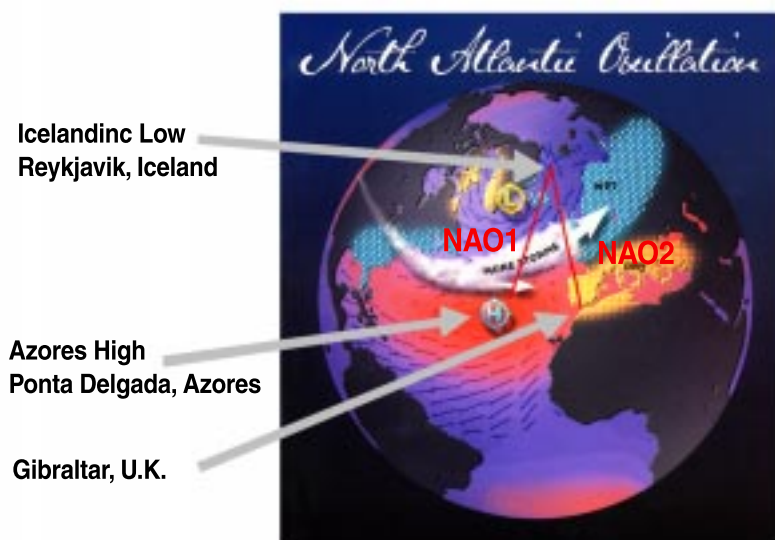

Icelandinc Low
Reykjavik, Iceland

NAO1

NAO2

Azores High
Ponta Delgada, Azores

Gibraltar, U.K.

FIGURE 3.6
Climate patterns when the winter NAO index is in positive phase. This illustrates alternative ways to estimate the North to South Pressure gradient over the North Atlantic. (e.g. NAO1 - SLP difference between Iceland to the Azores, and NAO2 - SLP dirrerence between Iceland and Gibralter). Adapted from http://www.ldeo.columbia.edu/NAO/.

The NAO index is positive when either the Icelandic Low results in a particularly low SLP, or the Azores High results in a relatively high SLP, or both. A negative winter NAO index results from relatively weak pressure gradients. A shift from a negative to a positive NAO index moves moisture up into Scandinavia, drawing from the Mediterranean. Positive NAO index phases are associated with increased heat and moisture flux to northern Europe, drought in the Mediterranean, and somewhat wetter conditions along the U.S. east coast (Figure 3.6).

The winter NAO index is a bi-pole, oscillating between two stable states (steep and weak pressure gradients) with periodic fluctuations of varying duration between the two, associated with large variations downwind in European climate. With a positive winter NAO index phase come significant changes in the frequency of Atlantic winter storms and different weather behavior in New England. Negative phases of the NAO index are associated with a reduction in the frequency of winter storms over the North Atlantic and dryer conditions along the New England coast.

Variations in the winter (December through March) NAO index are illustrated since 1864 (Figure 3.7) . The winter warming trend in southern New England coastal waters correlates well with the transition from a prolonged negative NAO winter index phase to a positive phase between 1950 and 1990 (Figure 3.7A).

About 49% of the variance in the winter temperature of the Northern Hemisphere over the past 60 years is associated with the Southern Oscillation Index and the winter NAO, with warm El Niño conditions in the Equatorial Pacific and positive winter NAO index phases associated with warmer winters. Variations in the winter NAO are also associated with larger-scale climate variability around the Arctic with the NAO as a component of a larger feature they refer to as the Arctic Oscillation (AO) or Arctic annular mode.

The emergence of longer-period variations in the NAO, including a persistent negative winter NAO index period in the 1950s and 1960s is not well understood. From the perspective of a 350-year NAO reconstruction based on ice core records from Greenland, the recent increase in interdecadal variability with more persistent negative and positive phases in the NAO beginning around 1900 is unique.
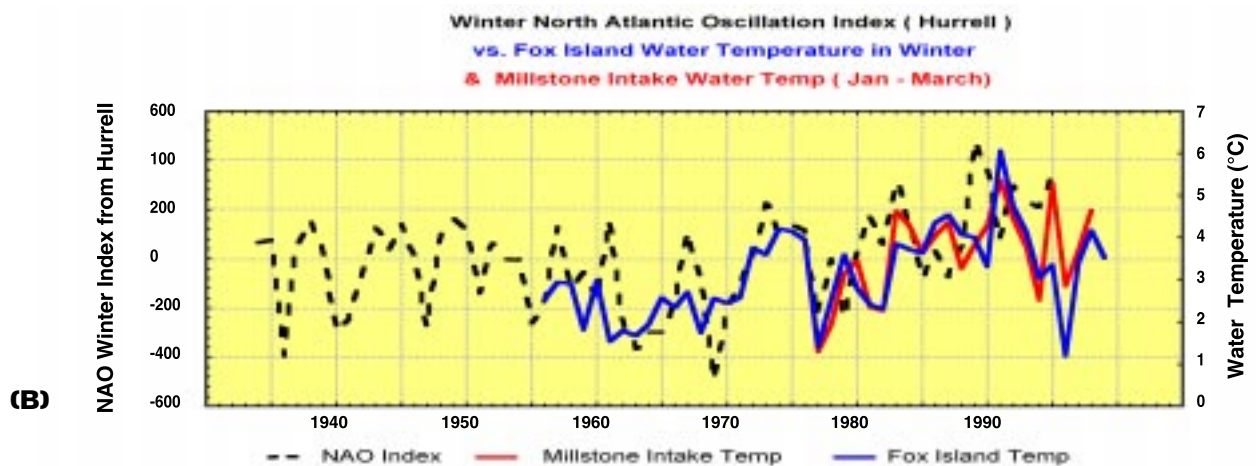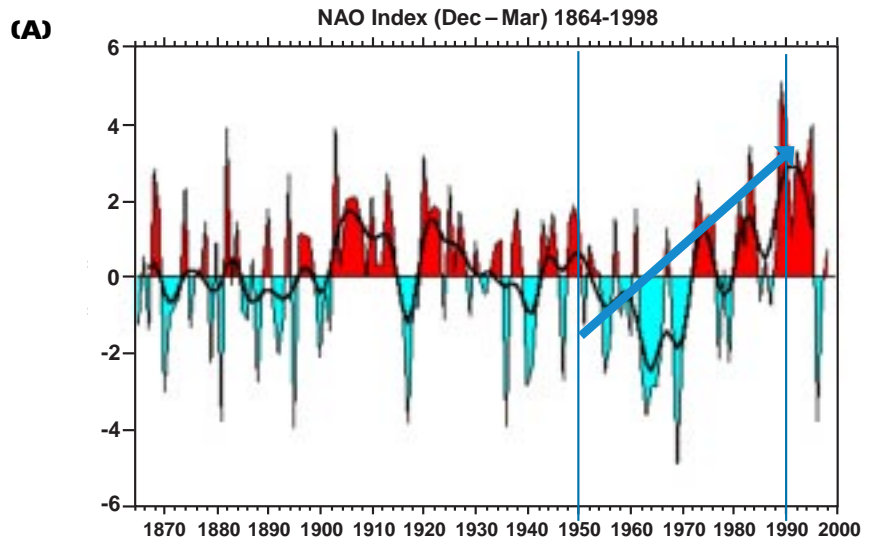
Summary and Discussion

A number of both natural and anthropogenic factors are known to influence the Earth's climate. Solar output, orbital variations, and volcanic eruptions have affected past climate variability and will continue to do so in the future. Land cover type influences how sunlight interacts with the Earth's surface, either reflecting the light back to space or absorbing it, resulting in warming or cooling (in the case of forests).

…there is a growing recognition that a significant component of the 20ᵗʰ century warming is due to emissions of greenhouse gases.

(A)

NAO Index (Dec – Mar) 1864-1998

FIGURE 3.7
The Winter North Atlantic Oscillation index plotted for 1864-1998 (A) and winter coastal water temperatures for southern New England (B). In (A) the red indices are positive, while the blue indices are negative. The arrow marks the warming trend between 1950 and 1990. In (B) the dashed line = winter NAO Index, the blue line = winter water temperature off Fox Island, Narragansett Bay, R.I., and the red line = winter temperature (Jan.-Mar. in Niantic Bay, CT) from Northeast Utilities Millstone Power Plant intake.

Winter North Atlantic Oscillation Index (Hurrell)
vs. Fox Island Water Temperature in Winter
& Millstone Intake Water Temp (Jan - March)

(B)

- - NAO Index — Millstone Intake Temp — Fox Island Temp

Human activities often result in the alteration of the natural land cover or in the emission of greenhouse gases, factors known to affect climate. Variations in atmospheric pressure systems, such as the North Atlantic Oscillation (NAO), are also known to influence weather and climate patterns in the Northern Hemisphere, including the New England region. All of these climate forcings interact to produce our ever-changing weather and climate.

We are currently in a period of rapid climate warming (e.g. the ten hottest years since the beginning of the last millennium have all occurred since 1983). How much of this recent warming is attributable to anthropogenic factors is still actively debated, but there is a growing recognition that a significant component of the 20ᵗʰ century warming is due to emissions of greenhouse gases.

We have also learned that the climate is a dynamic system which exhibits bounded instability and can jump between different stable states. We know that many natural processes can force the climate, and that several anthropogenic factors also can force the climate. Since we have no control over the natural forcings (solar output, volcanic eruptions, ENSO/NAO patterns), but do have control of many of the anthropogenic forcings (greenhouse gas emissions, land cover changes), it is only prudent for us to begin to consider ways in which the future impacts of anthropogenic forcings can be reduced.